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A Survey Assessment of International Composite Materials With Emphasis on the USSR

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Scientific and Technical Intelligence Committee

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STIC 83-013
November 1983

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This report was approved by the Scientific and Technical Intelligence Committee on 8 September 1983.

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Preface

This document was prepared by the Structural Materials Working Group of the Science and Technology Intelligence Committee (STIC). The assessment was prepared in response to STIC tasking requesting both a composite materials assessment and a collection guide on Soviet capabilities. The effort was expanded beyond the STIC tasking to include worldwide capabilities because the Working Group felt that such a document would be beneficial to a wider audience by providing information not otherwise available under a single cover. Further, the document will provide the framework for updating the comparative worldwide composites effort; such a comparison was previously possible only by review of several documents. Of necessity, discussions of some areas are brief and a degree of unevenness in coverage exists; however, comparative assessments between nations should be facilitated. For this study, US information is handled separately from the rest of the Free World.

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Aeronautical Systems Division; and by Messrs. William Schulz, David Roselius, and Robert Rapson of the USAF Wright Aeronautical Laboratories in providing information on composites technology in the Free World. The graphics for the report were prepared by the USAF Foreign Technology Division.

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A Survey Assessment of International Composite Materials With Emphasis on the USSR

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Key Judgments

The United States can no longer consider itself to have a dominant lead in composites technology; we are engaged in an aggressive worldwide competition to develop and apply these materials. The capability and goals expressed by Western Europe, Israel, Japan, the USSR, and China suggest that any lead achieved by a nation will be short lived 25X1

The Soviets are generally equal to the United States in composite materials design capability. They lag the United States by two to three years in the application of nonmetallic composites. Metallic composites applications are not yet widespread, but the Soviets lead the United States by four to five years in research on metallic composites. 25X1

The principal Soviet deficiencies in composite materials capability are a lack of automated equipment and a shortage of skilled technicians. Efforts to overcome these deficiencies could prove successful by the early 1990s, affecting weapon systems designs at that time. 25X1

The Soviet composites effort is principally directed toward aerospace structures, although applications to ground weapons and ship hulls have also been noted. Examples of Soviet claims include application to control surfaces and other components of fighter aircraft (MIG-27 and another new MIG), bombers (TU-22M), transports (IL-86, AN-72), helicopters (KA-26), tanks (T-72), and minesweepers (460-metric-ton Sonya class). 25X1

Soviet weapon systems of the 1990s will show gradual performance improvements as a result of composites applications; more dramatic performance increases can be expected in weapon systems of the 2000s as designer confidence grows and manufacturing deficiencies are overcome. 25X1

While Soviet projections for fighter aircraft composites applications in the 1990s reach as high as 50 percent of airframe weight, a more likely level of application is 35 percent. Soviet production of composites parts in standard "metal" shapes, to accommodate an unskilled work force, will limit the benefits of composite application. 25X1

The traditional Soviet persistence in program commitment could allow them to overtake US capability; for example, a reported Soviet program to produce a large, all-composite wing for a large Antonov cargo aircraft could, if successful, exceed the capability of current US programs directed at relatively small-size applications. US studies of large-size composites structures are scheduled to begin in late 1983. 25X1

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Table 1
Characteristics of Composite Materials for Aerospace Usage

Item	Effect	Approximate Payoff
Advantages		
Substitute composites for metals	Reduces weight 30 to 40 percent	Increase range 50 percent or increase payload or save fuel
Optimize design for composites	Improves aerodynamics and reduces weight	Increase range 85 percent and decrease turn radius 40 percent
Improved fatigue resistance	Longer part life and less damage susceptibility	Lower life-cycle costs
Dimensional stability	Accurate pointing and optics	Improved space-based systems
Replace metals	Conserves strategic materials	Up to two for one
Reduced electrical conductivity	Possible reduction in radar cross section	Improved survivability electronic warfare countermeasures
Disadvantages		
Organic matrix temperature limit	Structure must be below 200°C	
Moisture absorption	Temperature limit may be lower	
Reduced electrical conductivity	Possible loss of ground planes for avionics	
Expense of metal matrix	Significant cost increase	
Fiber/matrix interaction	Instability at high temperature	
Directed-energy weapon interaction	Potential increased susceptibility not fully understood	

[redacted] 25X1

Very few Soviet composite material claims have been confirmed [redacted] 25X1 25X1 We have no reason to disbelieve the Soviet claims [redacted] 25X1

Other nations are actively taking advantage of US composites research and development to rapidly improve the state of the art of their aerospace industries, sometimes even before the United States applies this technology. China has embarked on an aggressive composite materials program, but remains 10 to 15 years behind the United States [redacted] 25X1

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Introduction

The term "composites" refers to a wide variety of materials that share a common characteristic: two or more identifiable substances consolidated to form a heterogeneous, highly directional material (figure 1). Fiberglass is a commonly used term for a family of composite materials that are broadly applied to a wide variety of commercial and military products. In this study we have limited ourselves to those composites that consist of a fiber reinforcement in a continuous matrix, materials which are rapidly increasing in use throughout the world. Examples of fiber materials are glass, graphite, boron, aramid (Kevlar), and ceramics (silicon carbide). Examples of matrix materials include organic polymers, metals, ceramics, and carbon. The progressive development and application of composites are based on active programs in every highly industrialized nation.

Composite materials differ from most other common structural materials in that they are tailored to an application and are generally not identifiable as a material unit until the component has been completely fabricated. As a rule, most metal structures begin as a monolithic mass that is then further processed into the final configuration by various forming operations followed by machining. Composites are built up from a combination of reinforcement material and matrix to a shape that is generally in the final form. Less machining is required for composites than is performed on metal structures. The composite material becomes an identifiable material after the consolidation step. However, the specific steps are different for each type of material.

The benefits of composites over metals derive from the specific strength (strength divided by density) and from the specific stiffness of these materials as well as from the fact that a single composites part can often be fabricated to replace several parts of a built-up metal structure. The first two characteristics may be used to reduce the weight of a structure by as much as 50 percent; for example, over 115 kilograms (kg) can potentially be saved by fabricating the fourth stage of the MX missile out of graphite/epoxy instead of metals, resulting in the option to add one reentry vehicle, to extend range by 5 percent, or to improve reentry vehicle dispersion by 12 percent. The last composite material characteristic may be used to reduce the part count of a structure (the composites B-1 horizontal stabilizer test article had 40 percent fewer substructure parts and almost 60 percent fewer mechanical fasteners than did the metal structure); this savings can result in significant cost reduction (15 percent for the B-1 stabilizer) even though the materials used are much more expensive than conventional metals. 25X1

The principal benefits obtained from composites application are in primary structures: the aircraft wing, fuselage, and empennage; ship hulls and superstructure; mobile bridges for water crossings; and so on. 25X1
For these applications, the materials problems are difficult: materials must be thoroughly characterized in order to allow the design team to precisely calculate each element of structure; chemical stability over time is imperative and requires long-term experimentation. Dimensional stability is also essential as are the resistance to heating and aerodynamic erosion. Ease of fabrication is desirable to avoid excessive cost that would limit application. Finally, the suppliers must be able to guarantee delivery of materials of consistent quality. 25X1

Acceptance of composite materials by design teams is as important as material quality and availability. The use of composites is not simply a question of substituting the composite material for metal, but of completely redesigning each component to profit from the directional (or multidirectional) characteristics of the composite being used. 25X1

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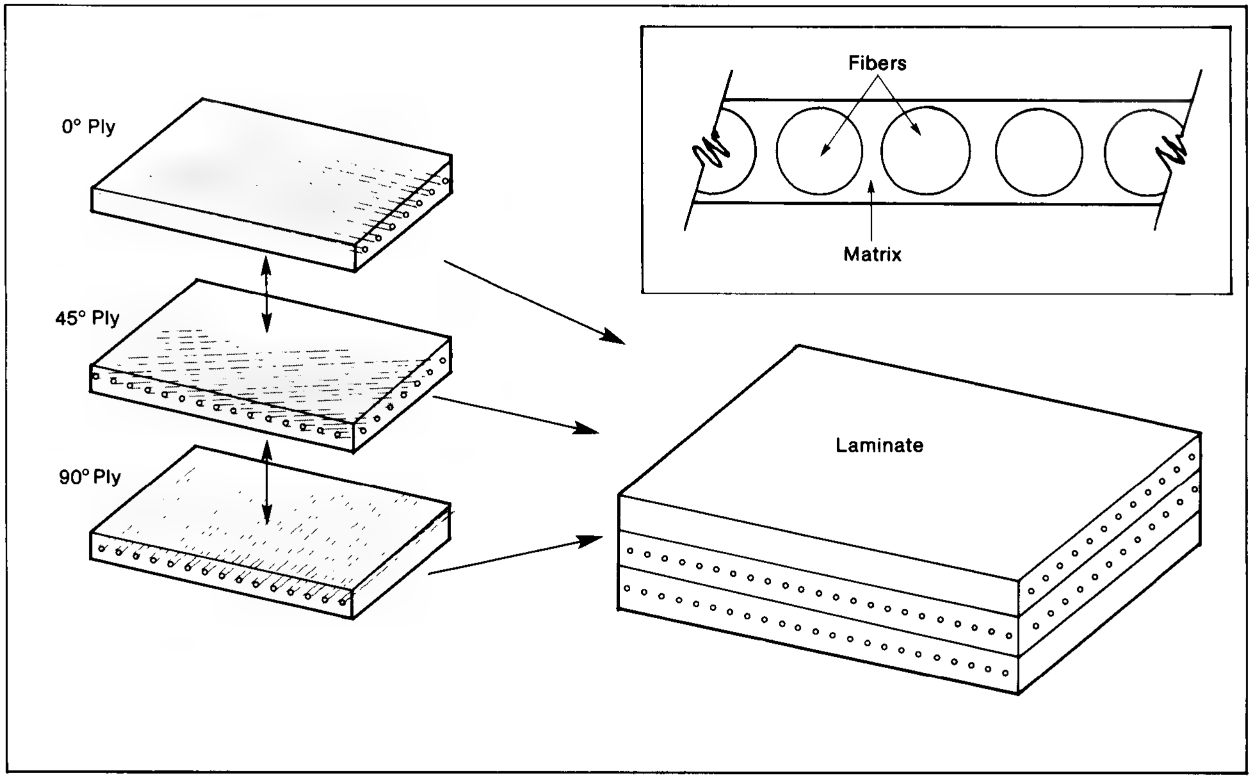

Figure 1. Composite Material Schematic 25X1

Although composites materials applications can result in desirable performance benefits in weapon systems, they are not, for the most part, essential to the production of future weapon systems. Alternative material choices, improvements in conventional materials, and doctrinal philosophy can also accommodate many performance improvement needs

Soviet Experience and Activity

Soviet research on composites started slowly in accordance with the typical conservative Soviet approach to new technologies. Thus, while the first US glass fiber production plant was built in 1928, the first Soviet glass fiber plant was not built until 1941. Likewise, Soviet research on carbon/carbon materials began in 1963, but it was not significant until US literature provided the impetus for an increase in the Soviet effort in 1978. One area of composites that did not follow the lead of Western researchers was metal matrix composites (MMC); by 1970 several Soviet MMC materials had been fully characterized and a few apparently were in production. In 1975 the Central Committee of the Communist Party of the Soviet Union declared that the highest technical priority of the 10th Five-Year Plan (1976-80) was the development of plastics and composites. The emphasis on composites appears to have continued to the present. 25X1

The decision to emphasize composites in the USSR was based upon four factors. First, composites reduce weapon systems weight, which results in improved performance. Second, composites are inherently fatigue resistant. Third, the use of composites can conserve strategic metals. Fourth, the United States was ahead in composites technology. Once the decision was made to emphasize composites, the Soviet composites program significantly expanded; thousands of scientists and engineers at more than 30

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facilities were assigned to the program; Western literature, conferences, and equipment were further exploited; and various components were flight-tested. As a result of this increased emphasis, the technology gap began to close.

Current Status

In discussing the current status of worldwide composites technology, the format was chosen to facilitate the direct comparison of the current state of the art with much of the emphasis on the USSR. The report discusses each area of composites technology as a separate activity in the USSR, the United States, and the Free World. The topics discussed are fibers, organic matrix composites, metal matrix composites, ceramic matrix composites, carbon/carbon, manufacturing, and applications. Because of the limited data available on China and Eastern Europe, those nations are briefly discussed.

Fibers

The reinforcement material in composite materials may be fibers, whiskers, or particles, and the matrix may be an organic, metal, or ceramic type of material. Arrangement of the fibers to give directional strength and stability (thus weight savings) is one of the many qualities making composites attractive to the aerospace industry. This section reflects the available data on various fibers (glass, boron, graphite, carbon, ceramic, and Kevlar) and current developmental research and the production capabilities in the United States, the USSR, and the Free World. 25X1 25X1 25X1

USSR Fibers. Soviet boron fiber production was reported in 1978 to be approximately equal to that of the United States; however, the Soviets claim to have already converted to producing boron fiber by depositing the boron on a graphite substrate rather than the standard, more expensive tungsten substrate. If true, this is a significant improvement over US capability. The Soviets also have the ability to produce silicon carbide, borsic alumina, zirconia, and boron nitride fibers. We believe that their production is limited. Steel fibers are also produced, but the production rates are unknown. We believe that steel fibers are probably produced on a relatively large scale. Other fibers—for example, carbon and aramid—are produced on an even larger scale. 25X1

In 1979 the Soviets began producing their version of Kevlar-49 at a rate of 1,000 kg per month, and they project overtaking current US production capacity of approximately 20 million kg per year by 1985. The Soviet fiber is said to be about 10 percent stiffer and 15 percent stronger than DuPont's fiber and to have a smoother surface. A smoother surface reduces the detrimental effects of moisture but provides poorer fiber-matrix interaction resulting in less matrix strength. In addition, the USSR has had large-scale production of several lower-grade aramid fibers for tires and garments for many years. 25X1

As mentioned previously, glass fibers have been produced in the USSR since 1941 and glass/epoxy had found many uses in the Soviet economy by the late 1970s. Soviet glass fiber plants produce the most commonly used glass fibers, as well as a hollow fiber that could have radar-absorbing implications. With 25X1

the advent of the SS-16 and SS-20, the Soviets began filament winding large solid-propellant rocket motor cases

The most significant Soviet fiber progress has occurred with graphite fibers. Before 1975, Soviet production of graphite fibers amounted to several thousand kilograms per year for all grades. Currently the Soviets claim to be producing 500,000 kg per year of a polyacrylonitrile (PAN)-based fiber that is comparable to two US fibers, Toray's T-300 and Hercules's AS fibers. The Soviet capacity to produce this fiber is claimed to be 10 times as much as their actual production. In addition to their PAN-based fiber, which has a strength of 2.85 GPa and a stiffness of 284 GPa, the Soviets claim to have laboratory production of an aramid-based graphite fiber with a strength of 3.1 GPa and a stiffness of 531 GPa; this is both stronger than the strongest Western graphite and stiffer than the stiffest Western graphite fiber. However, Soviet researchers indicate that high processing costs and difficult handling have kept this fiber from reaching production status.

Most of the Soviet effort in ceramic fiber research and development appears to be in silicon carbide (SiC) fibers or fiber coatings. SiC is attractive as a fiber for use in composites because of its high tensile strength, hardness, chemical resistance, low density, and high resistance to loss of these properties at elevated temperatures (the melting point of SiC is 2,690° C). SiC is susceptible to oxidation at elevated temperatures, but the matrix in a composite would reduce this tendency

Soviet researchers have indicated that the cost to produce SiC fibers in the Soviet Union may be four to six times that required to produce boron fibers. In spite of this, SiC fibers are in semiproduction, probably at a plant in Kalinin. In the United States, SiC fiber costs are decreasing but are still greater than those for boron fibers. Only 10 to 15 percent of the SiC whiskers produced in the USSR are suitable for use in fabricating composites. Judged from the available literature, Soviet capabilities in the production and use of ceramic fibers for advanced composites seem to have changed little in the past three years. However, work is proceeding at a steady pace and is expected to continue to do so.

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US Fibers. Advanced composite materials, especially graphite fiber reinforced composites, are increasingly being used in the United States for both military and commercial structural applications. The majority of the graphite fiber used is produced by pyrolysis/graphitization of a polyacrylonitrile fiber precursor. The technology and facilities to produce PAN precursor reside almost exclusively in Japan and the United Kingdom. Over the past several years, the United States has become a leader in the production of graphite fiber; however, this has been accomplished in conjunction with the Japanese either through licensing arrangements or joint ventures. The majority of the PAN precursor used by the US graphite fiber producers is of Japanese origin. More specifically, the US Department of Defense (DOD) has requested that a plan be developed to ensure that, by 1986, at least two domestic sources are providing a minimum of one-third of the precursor used in the manufacturing of graphite fiber for military weapon systems. 25X1

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A projection of the US market for PAN-based graphite fiber, generated by Hercules, Inc., is shown in figure 2, and the current Free World production capacity of PAN-based graphite fiber (also generated by Hercules) is shown in table 2. Several observations can be made from this data. First, in 1982 the United States was the major producer of PAN-based graphite fiber, having more than half of the Free World capacity. Second, there may currently be a glut in the market; that is, the availability of fiber far exceeds the utilization. Third, the DOD requirements account for 40 to 50 percent of the total US market. This means that the graphite fiber business in the United States is very competitive, and the DOD is the dominant customer. 25X1

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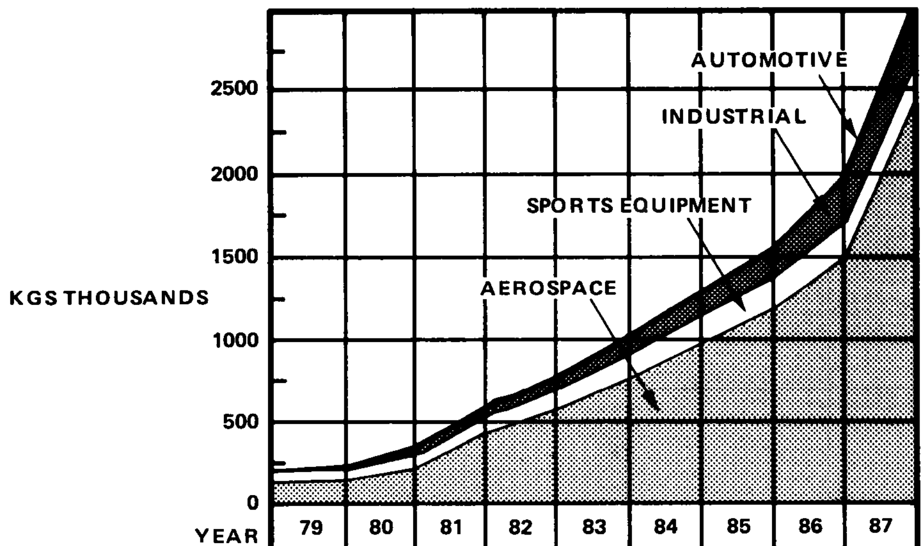

YEAR	79	80	81	82	83	84	85	86	87
AEROSPACE	100	170	380	516*	700*	880*	1100*	1350*	2400*
SPORTS EQUIPMENT	70	50	105	120	150	170	185	210	240
INDUSTRIAL	20	34	63	80	110	145	180	230	280
AUTOMOTIVE	2	2	2	2	4	13	20	32	45
TOTALS	192	296	550	712	964	1208	1485	1822	2965

* INCLUDES BOEING 767 DEMAND IN ITALY.

	82		83		84		85		86		87
DOD AS % OF TOTAL	41		43		47		50		51		37
DOD ANNUAL GROWTH %		37		37		27		30		10	

Figure 2. US PAN-Based Graphite Fiber Marke

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The major military systems requirements for PAN-based graphite fibers through 1988 is shown in table 3. These requirements include projected production scrap rates (buy-to-fly material requirements) and material estimates for spares and repairs. It should be noted that requirements for classified systems are not included. From this data, the projected military requirement for PAN-based graphite fiber in 1986 is approximately 450,000 kg. Assuming a 50-percent conversion factor, this translates to a PAN precursor requirement of 900,000 kg. Thus, in order to satisfy the DOD requirement, two domestic sources capable of producing a total of 320,000 kg per year of PAN precursor by 1986 must be developed.

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Various key US industries involved in composite materials development and production provided information on their corporate planning for domestic sources of materials. These companies included the three major graphite fiber producers (Union Carbide, Hercules, and Celanese), epoxy formulators (Hexcel, Hercules, Narmco, and Fiberite), and one textile grade acrylonitrile fiber producer (DuPont). To summarize the status of domestic PAN precursor, the following points can be made. There is currently one

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domestic source, Union Carbide, with a capacity of 900,000 kg per year. This capacity exceeds the requirement for one-third of projected 1986 DOD utilization. A possible second source, Celanese, with a capacity of 680,00 kg per year, may develop by the end of 1984; however, this source is not guaranteed. Increased US capacity will hinge on the DOD position for requiring domestic materials. [redacted]

Free World Fibers. France produces all the series of glass fibers including E, D, A, C, and S or R fibers. S or R glass fibers are the most expensive but possess the most desirable mechanical properties. Among the principal producers are: Saint-Gobain of France and Sielenka of Holland. In a related area, spun silica threads can reach a purity level above 99.9 percent and have remarkable ablation characteristics. They are made in France by Quartz et Silice. [redacted]

The acrylic fibers used in obtaining carbon fibers are known by a number of trademarks. Crylor is used for Rhone-Poulenc-Textiles (France), Courtelle for Courtaulds (Great Britain), Dralon for Bayer (Germany), and Orlon for DuPont (United States). These products are all made from polyacrylonitrile. [redacted] 25X1

In France, the Serofim company produces carbon fibers and high-modulus graphite fiber with the trademark "Rigilor" (from Crylor fibers). The fabrication is undertaken by a division of Carbone Lorraine. French production went from 4.9 metric tons per year in 1971 to 17.8 metric tons per year in 1982. The Rigilor fibers are called type AX for carbon fibers and type AG for graphite fibers and can take the form of continuous threads, bundles, cut threads, and even fabrics. This production is expected to cease in 1984 when Societe European Fibre Carbon (SEFC) begins producing 178 metric tons per year, and Societe Fibre Carbon (Soficar) begins producing 267 metric tons per year. [redacted]

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Pioneer work at the Royal Aircraft Establishment (RAE) in the United Kingdon in 1963 and simultaneous developments by Toray Industries in Japan led to the development processes for producing high-strength, high-modulus graphite fibers from PAN. The RAE process was patented and, in 1967, manufacturing licenses were issued to three British companies to produce the material. Courtaulds Ltd. was one of the three and is now the sole supplier of PAN and PAN-based graphite fibers in the United Kingdom. In Japan, Toray Industries and also Toho-Beslon, both large textile companies, produce PAN and PAN-based fibers.

In England, the Courtaulds company offers two types of fibers, called A or XA for carbon fibers and HT or HM for graphite fibers (trademark "Grafil"), which are fabricated from "Courtelle" fibers. Two production characteristics are peculiar to this company: pultrusion Grafil, which is a unidirectional shaped piece obtained by continuous molding of plastic reinforced with carbon fibers containing up to 65 percent by volume of Grafil in epoxy resin and is available in cross-sectional shapes and with variable dimensions; and fabrics of noncarbonized threads called "Grafil O" in the oxidation stage, which are assembled in several layers to be preimpregnated and carbonized during a single treatment. This procedure was used to make the carbon/carbon brakes of the Concorde SST. In 1982 the production by Courtaulds increased to 200 metric tons, and the target for late 1983 is 350 metric tons. Production capacity of RK Carbon Fibers, Ltd., in 1982 was 200 metric tons.

The Japanese chemical industry provides the basis for the strong interest in carbon fiber production in Japan. Several of the large chemical companies are actively producing carbon fibers or are developing the technology so that they can enter the market at the appropriate time. The currently popular precursor for carbon fibers, PAN, is produced in Japan by Toray Industries, Inc., Toho-Beslon, Sumitomo Chemical Co., Asahi Chemical Co., and Mitsubishi Rayon Co. These companies are competing with Courtaulds (United Kingdom).

Toray Industries, Inc., is considered the world leader in production of PAN-based carbon fibers which are supplied to customers throughout the world. One of the largest customers is the Union Carbide Corp. (United States), which acts as a distributor to the United States. The Toray production rate in 1981 was 17.8 metric tons per month and was being expanded to 26.8 metric tons per month. The Toray technology for PAN-based carbon fibers has been licensed to Union Carbide, and a plant is being built to produce carbon fiber at the rate of 26.8 metric tons per month using Toray PAN precursor. The other supplier in Japan of PAN-based carbon fibers is Toho-Beslon, 25X1 which produces acrylic fiber at the rate of about 3,570 metric tons per month but only about 17.8 metric tons per month of carbon fiber made from PAN. By the end of 1982, this production rate was increased to 32 metric tons per month, which makes Toho-Beslon the largest producer in Japan. 25X1

Toray is also one of the world's leading producers of carbon fibers, with production of 1,260 metric tons for 1982; its brand is the T 300 fiber, which is used a great deal in aviation. Other well-regarded manufacturers of carbon fibers are Toho-Beslon (1,020 metric tons per year) and Asahi-Nippon (180 metric tons per year), both of Japan. Mitsubishi Rayon of Japan is using a British precursor to produce 120 metric tons per year. 25X1

Asahi Chemical Co. is another major supplier of polyacrylonitrile. Asahi claims to be one of the world's largest producers and the largest acrylic fiber produc- 25X1 er in Japan. The company has 10 research centers in Japan and has built a new plant in Ireland for spinning acrylic fiber. Asahi has been studying carbon fiber technology for several years, and they believe that they have developed special precursors that can be carbonized rapidly in both filament form and tow form to produce better mechanical properties. 25X1

Additional composite fibers are Kevlar-29 and -49. From the scant literature available, it appears Western Europe imports Kevlar from the United States

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(principal supplier, DuPont). However, both the Netherlands and Japan are believed to be nearing production of fibers equivalent to Kevlar-49. In another area, boron fibers have good compression and torsional properties but are difficult to machine. They are supplied mainly by AVCO of the United States, SNPE of France, and Bergoff of Germany.

Organic Matrix Composites

Polymeric materials have been of great interest for many years throughout the world as composite matrix materials. The most generally used matrix materials are polymers and epoxies, phenolics, novolacs, and esters. For use at temperatures above 150°C, materials of most interest are polyimides, bismaleimides, and other higher-temperature polymers. In many cases, polymer systems offer more desirable processing characteristics than the competing metallic materials.

USSR Organic Matrix Composites. The Soviets report many epoxy matrix systems for conventional fiberglass composites applications. These applications are for temperatures not exceeding 200° to 250°C for extended periods of time. This technology has provided the Soviets with the basis for the development of advanced, organic-matrix composites. For many applications, especially for military and aerospace systems, matrices must be able to operate in the 400°- to 600°C-temperature range for a minimum of 100 hours. The USSR has embarked on several research programs for the development of heat-resistant polymers via improvement of existing polymers and the synthesis of hetero-organic and novel carbochain polymers. These materials maintain their desirable characteristics at temperatures exceeding 250° C. Table 4 lists the maximum heat-resistance capability of several classes of Soviet polymers.

With the above polymers available for use in composites, the Soviets can produce many materials comparable to those found in the West. Although the reinforcement of all of these polymers has been discussed in open literature, the most common Soviet composites are combinations of glass, aramid, boron, or graphite fibers and epoxy or phenolic resin matrices. As in the United States, graphite/epoxy is the most common of the advanced composites in use.

US Organic Matrix Composites. Organic matrix composite systems found early use in rocket motor cases and have been utilized on almost all new aircraft weapon systems developed since the late 1960s. The primary matrix systems utilized to date have been the high-performance epoxies. These systems have been effectively utilized with boron, carbon/graphite, glass, and Kevlar fibers in both primary and secondary air vehicle structures. The basic chemistry, control of cure, and processing of these systems have developed to the point where these materials are accepted for production use.

Most organic matrices used to date are limited to applications where the temperature does not exceed 150°C for long periods of time. In effect, this temperature limits the application of organic materials to vehicles flying at speeds of Mach 2.2 or less. To overcome this shortfall and extend the usefulness of composites to the next generation of advanced tactical aircraft, the DOD and industry have focused on a new family of resin systems, the bismaleimides. Current approaches are to modify the bismaleimide systems to process in the same manner as current high performance epoxies while achieving an increase in useful temperature capability to about 175°C. All major airframe contractors are pursuing this matrix system for the Advanced Tactical Fighter baseline structure.

Considerable interest has also been generated over the past two years in the area of thermoplastics to provide composite systems with vastly improved impact resistance and toughness. Primary emphasis is on polyetheretherketone (PEEK), a crystalline material, which, in addition to offering an order of magnitude increase in toughness over high-performance epoxies, provides solvent resistance to standard aircraft fluids. This property was lacking in earlier thermoplastic systems but not in standard epoxies. PEEK has a useful temperature capability of about 155°C. Based on continued success, PEEK or similar thermoplastic systems could be available for routine structural application as early as the 1985-87 time frame. 25X1

Higher-temperature matrix systems research and development is primarily concerned with two polyimide 25X1 materials developed by NASA, the HR-600P acetylene terminated material and polybenzimidiazole (PBI). These systems are usable at temperatures from around 260°C for the NASA systems to 370°C for PBI. Development work on these systems has centered on engine and tactical missile usage. They have not achieved routine application because of material cost and processing difficulties. The HR-600P, a new version of acetylene terminated imide, offers some promise of easing the process/fabrication difficulties through a unique approach that allows initial use under epoxy conditions. Although interest in the area of high-temperature organic systems is being main- 25X1 tained, the progress, as measured by application, is slow. 25X1

Free World Organic Matrix Composites. Development of organic matrix composites in the Free World has been characterized by much interchange between the United States and other nations. Ciba-Geigy of Switzerland and Rhone-Poulenc of France supply many of the basic chemicals that form the matrices. France has developed several high-temperature polymers that are competitive with polyimides as matrix materials. In addition, US companies and their subsidiaries provide large quantities of prepregs to most Free World nations. Because of the interchange with the United States, Free World organic matrix com- 25X1 posites capabilities can be considered as paralleling that of the US organic matrix composites. 25X1

Metal Matrix Composites

Metal matrix composites are materials that consist of a metallic matrix that is reinforced by a stronger or stiffer material in the form of wires, fibers, filaments, whiskers, or particulates. This section will treat only

those composites for which the reinforcement is continuous filaments or fibers. With the advent in the early 1960s of newly developed fibers intended for use in organic matrix composites, it was a natural consequence that the use of these fibers to reinforce metallic alloys would be attempted. Early efforts dealt with the more difficult problems associated with the processes by which fibers could be introduced into a metal matrix and with the evaluation of potential improvements in high-temperature strength that were expected for MMCs. As a result of a US DOD initiative, renewed interest in the potential of MMCs now exists, offsetting some early results that were not very encouraging and opening new possibilities for application to a wider variety of weapon systems. [redacted]

USSR Metal Matrix Composites. The Soviet MMC effort includes fibrous composites, eutectics, and dispersion strengthened materials. Although the effort covers such relatively low-cost material systems as steel/aluminum and boron/aluminum, the major thrust appears to be to provide materials with the capability for extended usage at elevated temperature. [redacted] the Soviet MMC effort appears to be about two-thirds of their composites research, although the epoxy matrix composites have reached a higher state of development; approximately 13,000 kg of boron fiber goes into the MMC effort yearly (95 percent of USSR boron fiber output in 1978). [redacted]

Four reasons have been given by the Soviets for their interest in MMC. First, composites are inherently fatigue resistant so that critical structures will last longer when composites are used instead of conventional metals. Second, the improved specific properties of composites over metals result in conservation of strategic materials. Third, the reinforcing fibers can provide better high-temperature characteristics for the matrix metal by supporting the matrix as it softens. Fourth, many standard metals fabrication techniques are directly applicable to MMC. The lower cost and greater strategic material conservation obtainable from fiber-reinforced plastics might be offset by not having to develop new fabrication techniques or labor skills for MMC. This is particularly attractive to the Soviets because of shortages of skilled labor in the Soviet work force. [redacted]

The Soviet MMC program shows strong basic research and exploratory development. A significant advanced development effort is evident and limited production is probable. Two technical areas that have not received much coverage until the late 1970s in Soviet literature are foreign object damage (FOD) and nondestructive testing/quality control (NDT/QC). These two areas must be addressed by the Soviets before large-scale production of composites structures can occur; the recent appearance of a number of articles on FOD and on NDT may indicate that the Soviets are approaching production status on MMC structures and are now publishing results of previous research that was connected to possible applications. [redacted]

A further indication of Soviet interest in the production of MMC aircraft structures comes from Soviet technical literature and may be traced to the 1975 Paris Air Show, where the Soviets displayed a boron/aluminum panel to which extruded boron/aluminum stiffeners had been spot-welded. Since 1980, several researchers who have been identified with the Antonov Design Bureau have written extensively on the welding of boron/aluminum composites [redacted]

The Soviets MMC program has placed a heavy emphasis on fibrous composites with smaller efforts on dispersion strengthened composites and on eutectics. As in the case of nonmetallic matrix composites, the MMC effort seems to be aimed at increasing the temperature capability of aerospace structures. Figure 3 compares the US fibrous MMC research program to those fibrous MMC systems that have been identified in the Soviet research program. Several of the Soviet systems, including boron/aluminum and steel/aluminum, are currently in production. The Soviets have committed large resources to MMC continuously since the mid-1960s and have investigated at least 45 systems not studied in the United States; many of the efforts appear to be minor. [redacted]

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MATRICES \ FIBERS	CARBON	BORON	TUNGSTEN	STEEL	SiC	BORSIC	NICKEL	MOLYBDENUM	MAGNESIUM	BORON NITRIDE	Al_2O_3	SiO_2	ZrO_2	BERYLLIUM	HfO_2	TITANIUM	LEAD	NIOBIUM	B_4C	TaC	Al_3Ni	SiN	TiB_2	TiC	ALUMINUM
ALUMINUM	●	●	●	●	●	●	●	○		■	●	●				■	○		■		■	■	■	■	
TITANIUM	●	●	●	○	●	●		●	○		●			●				○	○				■	■	
NICKEL	●	●	●	●	●	○		●			●	○			○	○			■	○		■	■	■	
COPPER	●	●	●	●			○	●			●					○	○								●
MAGNESIUM	●	●		●	●						●			■		●			■				■	■	
SILUMIN (11% Si–89% Al)		○			○																				
NICHROME	○	○	○	○	●	○		○			●									○			■	■	
ALUMINUM–TITANIUM		○		○							○														
STEEL	○		○		■																				
CHROMIUM	○	○		○	○			○			○		○							○					
TUNGSTEN			■					■		○		■	■												
ZIRCONIUM	○																								
BERYLLIUM		○																							
COBALT	●	○		○	●			○			●									○		■			
SILVER	●		■	■							■											■			
BORON		○																							
LITHIUM	○	○			○																				
TIN																		○							
LEAD	●																								
NIOBIUM											■		■												
TANTALUM												■	■												

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■ US ONLY
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Figure 3. Fibrous Metal Matrix Composites

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US Metal Matrix Composites. Research on MMC in the United States was initiated during the late 1960s because these materials were viewed as being ideal for high-temperature, high-speed applications. However, as US interest in hypersonic aircraft waned, research in MMC rapidly tapered off. For almost a decade, US MMC efforts were restricted to a very small technical community working with a minimal budget.

In 1978, continued proddings from the US MMC community combined with indications of a large MMC effort within the USSR, caused the initiation of an accelerated US demonstration program in these materials. While not as extensive as the apparent Soviet program, the US effort has made significant progress in the last five years. While US understanding of the fundamental aspects of the materials may not be as detailed as that of the Soviets, the United States could actually attain large-scale production in military systems first. Significantly, the new US program has included potential MMC applications in many fields—for example, spacecraft, armor, and torpedo boats—that do not involve high-temperature capabilities.

Figure 3 measures the breadth of the two programs but does not reflect relative quality or timing of research. In general, the Soviet research is aimed more toward a scientific understanding of the materials, while the US research takes an empirical engineering approach. Currently, the US effort also includes an intensive effort in whisker and particulate reinforcements as well as the fibrous MMC effort. 25X1

Free World Metal Matrix Composites. MMC research in Europe and Japan was relatively slow in starting. However, with the obvious interest in these materials being shown by both the United States and the USSR, the rest of the world soon began similar research. 25X1 25X1

Because information on US MMC research has been closely controlled since 1979, much of the Free World effort is duplicating earlier US work. Fibrous MMC research appears to be primarily concerned with boron/aluminum and with silicon carbide/aluminum, although the British have also studied copper matrix composites. Applications of fibrous MMC are probably several years in the future. Whisker and particulate reinforcements have also received attention; Japan displayed particulate MMC applications to automotive engines at the Fourth International Conference on Composites Materials in Tokyo in October 1982. A comparison of the US and Japanese MMC programs is provided in figure 4. 25X1

Ceramic Matrix Composites

Ceramic materials possess properties that make them attractive for a broad range of applications, especially at higher temperatures. Ceramic matrix composites offer the potential for improved performance by reducing the tendency toward catastrophic failure found in monolithic ceramic materials. Such composites, especially when reinforced with continuous lengths of ceramic fiber, exhibit dramatically improved fracture toughness and failure resistance. These materials also maintain their strength to very high operating temperatures, exhibit low densities, and low thermal expansion coefficients. They are inherently oxidation resistant without dependence on strategic elements or coatings and possess potentially exploitable electrical properties. 25X1 25X1

USSR Ceramic Matrix Composites. As in the United States, Soviet ceramic matrix composites appear to be several years from production. Currently, the primary technical difficulty is in the processing of the ceramics. Although research is being done on the use of 25X1

MATRICES \ FIBERS	CARBON	BORON	TUNGSTEN	STEEL	SILICON CARBIDE	BORSIC	NICKEL	MOLYBDENUM	BORON NITRIDE	ALUMINA/SILICA	ZIRCONIA	HAFNIA	TITANIUM	SILICON NITRIDE	TITANIUM DIBORIDE	TITANIUM CARBIDE
ALUMINUM	●	●	●	●	●	●	■		●	○	○	○	■	●	●	●
TITANIUM	●	●	■		●	●		■	○						■	■
NICKEL	●	■	●	■	●			■							■	■
COPPER	●	●	■	■	○			■		○						
MAGNESIUM	●	●		■	●					○			■		■	■
NICHROME	○		○		●										■	■
STEEL			○	■			○	○								
CHROMIUM			○				○	○								
COBALT	■				■		○	○						■		
NIOBIUM							○				■		○			
TANTALUM							○				■					

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Figure 4. US and Japanese Metal Matrix Composites Activity 25X1

various reinforcements in silicon nitride; in carbides of silicon, aluminum, zirconium, niobium, and hafnium; and in oxides of silicon, aluminum, and zirconium, the processing of the matrices within the USSR has thus far yielded materials with unacceptably high levels of impurities.

US Ceramic Matrix Composites. Recent research results for matrix composites have been very encouraging. Silicon carbide fibers (obtained from Japan) have been incorporated into glass and glass/ceramic matrices with significant improvements in strength and toughness. An exploratory development effort is now under way to develop a domestic source for silicon carbide and silicon nitride fiber. Once the capability of making satisfactory fiber is established, additional effort will be directed toward composite development. The United States appears to be from two to three years behind Japan. Potential uses of ceramic materials in applications are outlined in table 6 in the US Applications section. 25X1 25X1

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Free World Ceramic Matrix Composites. Free World ceramic matrix composites information is limited. It has been reported that Japanese efforts to develop ceramic matrix composites have made good progress, but details on specific fiber and matrix materials are sparse. Silicon carbide fibers made from a silicon polymer precursor represent a significant advancement in ceramic reinforcements, and at the present time the only commercial source of such fibers is Japan. In addition to the MMC application in automotive engines mentioned above, the Japanese (and also Volkswagen of Germany) are applying ceramic composites to the pistons of these engines. [redacted]

Carbon/Carbon

The term carbon/carbon is a term that is applied to all types of composites in which a carbonaceous matrix is reinforced with a carbonaceous fiber. Variations in fiber structure and matrix formation and heat treatment can result in a wide range of properties, depending upon the degree of graphitization that is inherent or induced in the materials through processing variations. A desired balance of properties can be achieved by judicious selection of a processing method to suit the specific application. There is no single carbon/carbon composite that serves all applications. [redacted]

The processing variations and their relative merits could be discussed at great length, but the state of the art is changing so rapidly that old methods are being replaced by new modifications frequently. The reason for this dynamic situation is that the number of variables which can influence the final product are so numerous that the materials are continually being upgraded as more information is gathered about their behavior. [redacted]

USSR Carbon/Carbon. The USSR has embarked on a program to develop carbon/carbon composites. [redacted] While the Soviets can produce two-dimensional carbon/carbon in quantity, they are still having some difficulty with three-dimensional material; Soviet researchers have repeatedly questioned US experts about the necessity to develop carbon/carbon materials with fibers in more than three directions and about the manufacturing technology necessary to fabricate these materials. [redacted]

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The Soviets are investigating carbon/carbon rocket nozzle throats [redacted]

US Carbon/Carbon. US carbon/carbon technology was initially advanced through Air Force funding. Many variations of process technology were examined in the course of that program. Fiber size and distribution received much attention because of the need for improved ablation performance, properties, and fabricability. Rayon-base fibers (T-50) were eventually replaced with PAN-based (T-300) and pitch-base (VSB-32) fibers [redacted]

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In the early 1970s during the development of various carbon/carbon preforms, the need for automation in the weaving process became apparent. This led to the development of several proprietary weaving machines by US companies [redacted]

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For special-purpose applications such as improved erosion resistance and radiation hardening, additions of other elements or compounds to the fiber, or to the matrix, or to both are being investigated. Organometallic compounds capable of being converted into refractory carbides and solution impregnation of halides result in heavy metal carbides that enhance the erosion resistance and provide some decrease in nuclear vulnerability. This type of program might explain the Soviet research in carbide reinforcement of carbon. The addition of silicon in the process also can result in the formation of silicon carbide, which increases the oxidation resistance of carbon/carbon materials

The nose cap and the leading edges of the space shuttle wings and vertical stabilizer are examples of carbon/carbon composites application that suggest a significant US lead in this technology. No similar uses of such materials are evident elsewhere in the world. Improved composites and coatings are being developed in order to test the feasibility of using carbon/carbon composites for gas turbine engine components. If successful, it is anticipated that significant performance improvements will be realized in cruise missile propulsion systems

Free World Carbon/Carbon. In the mid-1970s much of the US carbon/carbon technology was purchased by the French; the major French companies involved were Societe Europeene de Propulsion (SEP), Aerospatiale, and Brochier et Fils. The strong French weaving background has enabled them to rapidly acquire the technology to build their own machines, which are remarkably simple in operation and have the capability to weave contoured preforms for rocket nozzles up to 1.5 meters in diameter. While the French carbon/carbon weaving capability may be the best in the world, they still rely on the United States for most analysis and testing. French carbon/ carbon applications include aircraft brakes, rocket nozzles, reentry vehicle nosetips, and prosthetics. In recent years the Japanese have shown an interest in acquiring carbon/carbon technology from both France and the United States, but no applications have yet been indicated.

Manufacturing Capability

Industry has developed using manual placement of fibers in the desired directions for the fabrication of composites components. Automation of some operations (plycutting and tape laying) has been adopted in some segments of US industry, but the industry is generally still dependent on the availability of trained labor. The basic equipment used in fabricating composites has widespread use in various fields, including textiles and medicine, but the technical know-how of using the equipment for composites is less widely understood. 25X1

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A special step in the manufacturing process is the inspection or nondestructive testing of composite components to assure a quality product. Similar to metals, several promising methods have evolved to inspect the final product. Among them are: ultrasonic, X-radiography, thermography, and acoustic emission 25X1

USSR Manufacturing. In composites, as in many other technologies, the USSR appears to be weakest in manufacturing. While the research institutes appear capable of developing the necessary techniques, the transition to large-scale production is often difficult. Western literature has been closely followed in the USSR to determine the best methods of fabrication of composites components. Thus, what little is known about composites manufacturing in the USSR closely resembles US practices in most cases. 25X1

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Early Soviet literature on nondestructive testing principally discussed acoustic methods, with an emphasis on acoustic emission. The Soviet claims, made in the mid-1970s, still exceed the US capability to locate flaws in small structures. Very recent Soviet statements indicate a shift in NDT emphasis to X-ray techniques. Fiber production in the USSR is monitored using X-ray shadow microscopy; this technique appears to be overly conservative and may account for a high scrap rate on fibers reported in earlier years by Soviet technologists. Techniques used for the NDT of laminates and shapes include visual thermography,

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ultrasonic scans, and filmless X-ray through transmission. The last technique is reportedly preferred and has a claimed capability of accurately detecting a 2 percent change in density at a scanning rate of 1 to 2 meters every 15 seconds. Multiple 100 to 200-keV X-ray sources are used to triangulate flaw location and depth. Research on filmless X-ray techniques in the United States has thus far been unsuccessful in detecting density changes of less than 6 to 8 percent.

In 1978, the Soviets purchased 40 autoclaves from a West German firm; the vendor described these autoclaves, which were 5 meters in diameter by 15 meters long, as being ideal for curing aircraft wing structures.

For the fabrication of MMC, the Soviets use at least five different techniques. Four of these techniques—hot rolling, vacuum pressing, liquid metal infiltration, and plasma deposition—are also used by other industrial nations. The last technique, explosive fabrication, has received much more emphasis in the USSR than in the United States. Explosive fabrication is attractive because it minimizes the amount of heat that normally would degrade the fiber-matrix interface during processing. Volgograd Polytechnic Institute, the Institute of Hydrodynamics in Novosibirsk, and the Electric Welding Institute *imeni* Ye. O. Paton in Kiev appear to be the three leading facilities engaged in this research, which has been going on for at least 10 years. The Soviets report that they are able to make complex shapes of large, semifinished components by this technique. Production of sheets, plates, shells, pipes, and rods has been specified in open literature.

While nothing has yet appeared in Soviet literature about the automation of composites fabrication, the Soviets appear to have an adequate capability to fabricate and inspect rather sophisticated composites structures. Even in the United States, the F-16 forward fuselage and the B-1 horizontal stabilizer were produced without automation. Thus, Soviet composites manufacturing technology is probably adequate to support the relatively widespread application of composites to various types of prototype systems. However, the Soviets could not efficiently support large production runs with their current work force and shortage of automated equipment.

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US Manufacturing. Composite structures production capability in the United States is widely varied, involving low-performance materials, such as fiberglass composites, and various high-performance composites, including organic matrix, metal matrix, and carbon/carbon materials. While fiberglass composites are widely applied to military systems, such materials do not usually involve advance procedures for production. Metal matrix and carbon/carbon composites are high technology, specialty materials that are currently produced in small quantities with very specialized processes involved.

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At this time there is an ample fiber supply capacity. Graphite fibers are produced by several companies that have sufficient capacity for current production needs. The scale-up of fiber production is straight forward and requires approximately 24 months' leadtime. Kevlar fibers are produced in very large quantities and are widely applied in aircraft, body armor, ship armor, sporting goods, tires, and other consumer products. DuPont has recently expanded Kevlar production to 20 million kilograms per year, and no shortages are foreseen. Boron fibers are a specialty product and are now produced solely by the Avco Corp. Boron production is very low, and the price is very high. Boron is used in metal matrix composites; some of the older organic matrix applications, such as the F-14 and F-15 empennage; and in some special structural areas where unique properties are required. The boron supply has been reliable, but the recent loss of the second source, CTI, was a direct result of a decreasing market, and the production of boron may eventually be jeopardized by economic conditions.

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No problems have been experienced in the supply of organic matrix materials and none are anticipated because the base material for most of these resins is petroleum. Specialized high-performance matrix materials are expensive, but suppliers can generally be found

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The qualified producers of aerospace composite structures are predominately the major prime contractors, although some subcontractors are now producing composite structures. There are numerous other companies that produce composite structures for low-volume applications such as spacecraft. There are also a number of small companies that manufacture specialized parts and are capable of producing limited military hardware. These small producers must be accounted for in the industrial base.

Composite production is routinely done on a one-shift-per-day basis. As a result, considerable excess production capacity exists without construction of significant new facilities. There are some capital equipment considerations which can pace a production scale-up, such as availability and scheduling of tape laying machines, tooling, and autoclaves; however, none of these are major factors at the current low rate of production.

Automation of the production of composite structures is in the first-generation stage. Major automation demonstrations have been accomplished by Grumman, Northrop, General Dynamics, Vought, and McDonnell. There is great promise in automation as a means to reduce the cost and to overcome much of the variability in composite details. The United States holds an apparent technological edge over the rest of the world in automating the production of these structures; however, the transfer of automation technology out of the country through commercial sales of tape laying machines and numerically controlled cutting machines could erode this technology lead.

Free World Manufacturing. Free World composites manufacturing capabilities have increased greatly by international agreements. The US Boeing Company has trained hundreds of Italian production personnel to produce composites structures for the Boeing 737, 757, and 767 aircraft. Similar, but less extensive, training programs are occurring with Belgium and Spain in support of F-16 production, with Canada and Australia in support of F-18 production, with Japan in support of F-15 production, and with the United Kingdom in support of AV-8B production.

France is probably the world leader in the manufacture of carbon/carbon materials. Brochier et Fils has collected all phases of the process into a single facility, unlike the US approach of having a specific facility perform a specific phase of the process. 25X1

While Japan may be the world leader in robotics, they have developed no automated composites facility like those developed by Northrop and Grumman in the United States. However, Japanese robotics expertise will undoubtedly be applied to composites manufacturing in the future. 25X1

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Applications

USSR Applications. Soviet composites applications are seldom identified in unclassified literature. Published conference papers, even for internal symposiums not attended by Westerners, are usually very basic and highly theoretical. 25X1

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The Soviet use of fiberglass has not been extensive but has paralleled US efforts in most cases. One application has been for ship structures. Naval applications include the hull structures of at least four classes of ships: the 90-metric-ton Yevgenya-class MSI, the 290-metric-ton Zhenya-class MSC, the Andrysha-class MSS, and the 460-metric-ton Sonya-class MSC. 25X1

The Soviets have imitated the United States in much of their reported aircraft applications. They have investigated hybrid laminates composed of graphite/epoxy and fiberglass/epoxy and have reportedly applied this combination to the floor beams of the YAK-40 and IL-62. Other reported hybrid uses are for engine components including fan housings, fan blades, and compressor blades. 25X1

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[redacted]

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[redacted] The ballistics coefficient (beta) is an indicator of RV performance and is a function of the RV configuration and mass. Historically, Soviet RVs have had lower betas than those of the United States. The trend in both the United States and the USSR is toward RVs with higher betas. [redacted]

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The Soviets are also using composites in ground weapons. Starting with the T-64 in 1965 and the T-72 in 1974, the Soviets introduced tanks with laminated armor in the upper glacis of the hull. While the exact arrangement and types of materials used in the T-64 are unknown, the upper glacis of the T-72 contains a glass-reinforced plastic (GRP) component (figure 9) that comprises a portion of the total armor system. [redacted]

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[redacted] The Soviets are also using Kevlar-type composite as body armor, as shown in figure 10. [redacted]

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The first use in the Soviet Union of composite materials for helicopter applications was made by the Kamov design bureau. In 1968, the KA-26 Hoodlum was deployed with GRP rotor blades. Since 1968, most new helicopters have had composite blades, and product improvement programs for older aircraft have included projects to replace metal blade designs with composites. Helicopters believed to have GRP rotor blades (or blade prototypes) include the KA-15, KA-25, MI-6, MI-8, MI-24, KA-26, and the new MI-26 Halo, a heavy-lift helicopter. Since the late 1960s, tail rotor blades of GRP have been regularly produced for the MI-6, MI-8, and MI-24 helicopters, and more recently for the MI-26. [redacted]

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Figure 9. Fiberglass Epoxy Armor Applications [redacted] 25X1

More advances composites for helicopters have also been considered by the Soviets. Development programs have included the use of higher performance fibers such as boron and graphite, especially in hybrid composite designs with less costly glass fibers. In 1977 the Soviets reported the investigation of graphite and glass hybrid composites for the longitudinal forward and rear webs of the rotor blades on the KA-25, which entered service in the 1960s. Full-scale dynamic tests indicated longer service life based on 21-million-cycle fatigue tests. Graphite-epoxy tail sections also have been evaluated, but test results and specific applications are unavailable. [redacted] 25X1

While very few Soviet composite applications have been confirmed, none of the reports cited above are inconsistent with the level of technical expertise that is evident in Soviet literature and in Western contacts with Soviet researchers. The breadth of reported applications would appear to indicate a Soviet capability to field composites components on various military and nonmilitary systems. [redacted] 25X1

Figure 10. Organic Fiber Body Armor [redacted] 25X1

US Applications. Almost from its inception, the US composites research program had flight tests and production applications as its goals. In the late 1960s, the Air Force established an Advanced Composites Advanced Development Program Office (ADPO) to direct the design, fabrication, and testing of composite aircraft components. Early efforts of the ADPO included a boron/epoxy F-15 wing, flight tests of 40 boron/epoxy F-4 rudders, a graphite/epoxy F-111 horizontal stabilizer, graphite/epoxy forward fuselages for the F-5 and F-16, and various pieces of secondary structure. The current US state of the art was essentially established by the ADPO in the mid-1970s with the design and construction of the horizontal and vertical stabilizers for the B-1. Since then, the ADPO has addressed missile and spacecraft applications. [redacted] 25X1

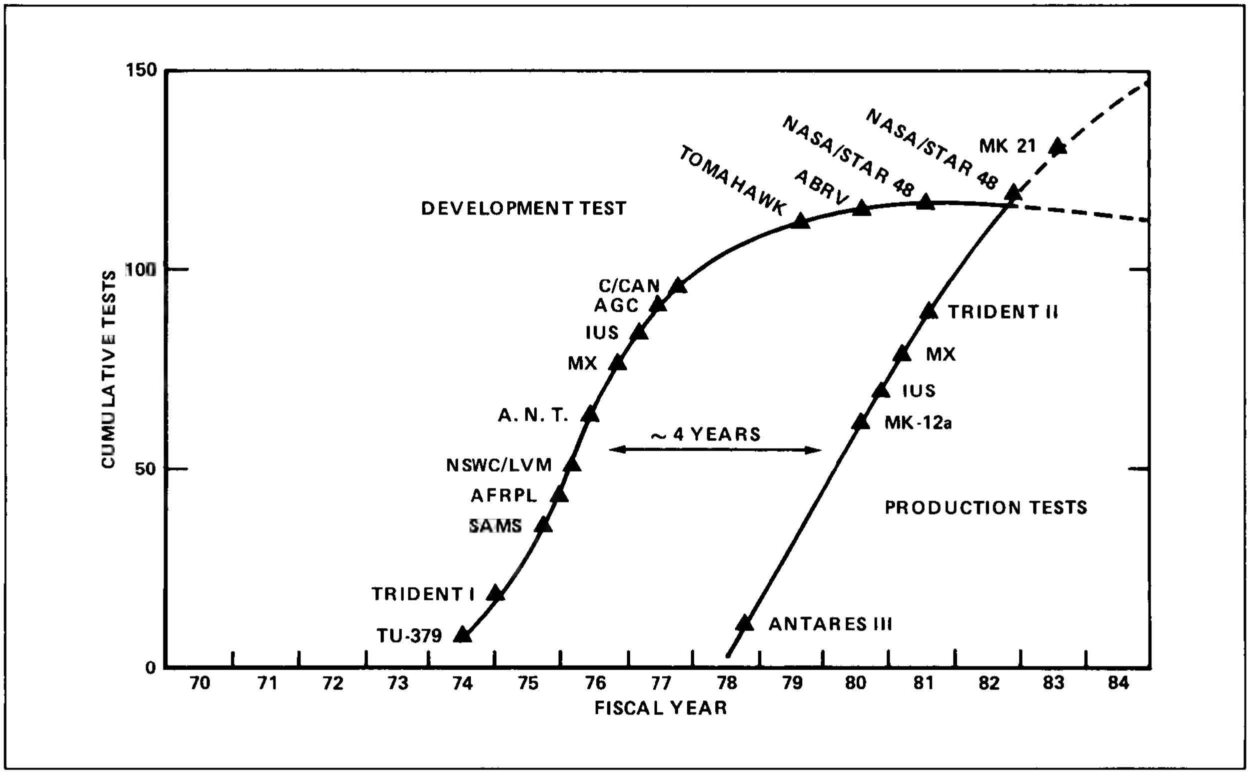

Figure 11. Strategic Missile Carbon/Carbon Nosetip and Rocket Nozzle Tests

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The United States has lagged the Soviet Union as well as the West European countries in adopting fiber reinforced composites for helicopter applications. Production of US composite components began in 1978 with parts for the Sikorsky CH-53E and Boeing-Vertol CH-46E aircraft. French and West German parts were produced in the early 1970s. The United States, however, will undoubtedly jump ahead by applying composites to primary structures. US programs to develop Kevlar/epoxy ribs, stiffeners, and skins for helicopter tail sections have been very successful. Prototype structures are now being planned for flight testing.

US composites components in production include F-14 horizontal stabilizers and overwing fairings, F-15 stabilizers and speed brakes, F-16 stabilizers, F-18 wing skins and some secondary structure. In addition, 25 percent of the AV-8B and some space shuttle and Trident missile components are composite materials.

The first civil aircraft to use advanced composites extensively in its primary structure, the Lear Fan, represents a fundamental departure from conventional design practice. Graphite/epoxy and Kevlar/epoxy account for over 70 percent of the aircraft's structural weight, with the remainder taken up by hardware, fittings, windows, and the landing gear. Because of certification disputes involving Lear Avia and the Federal Aviation Administration, the Lear Fan is being produced in Ireland.

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The US applications of carbon/carbon and MMC are summarized in figures 11 and 12, respectively.

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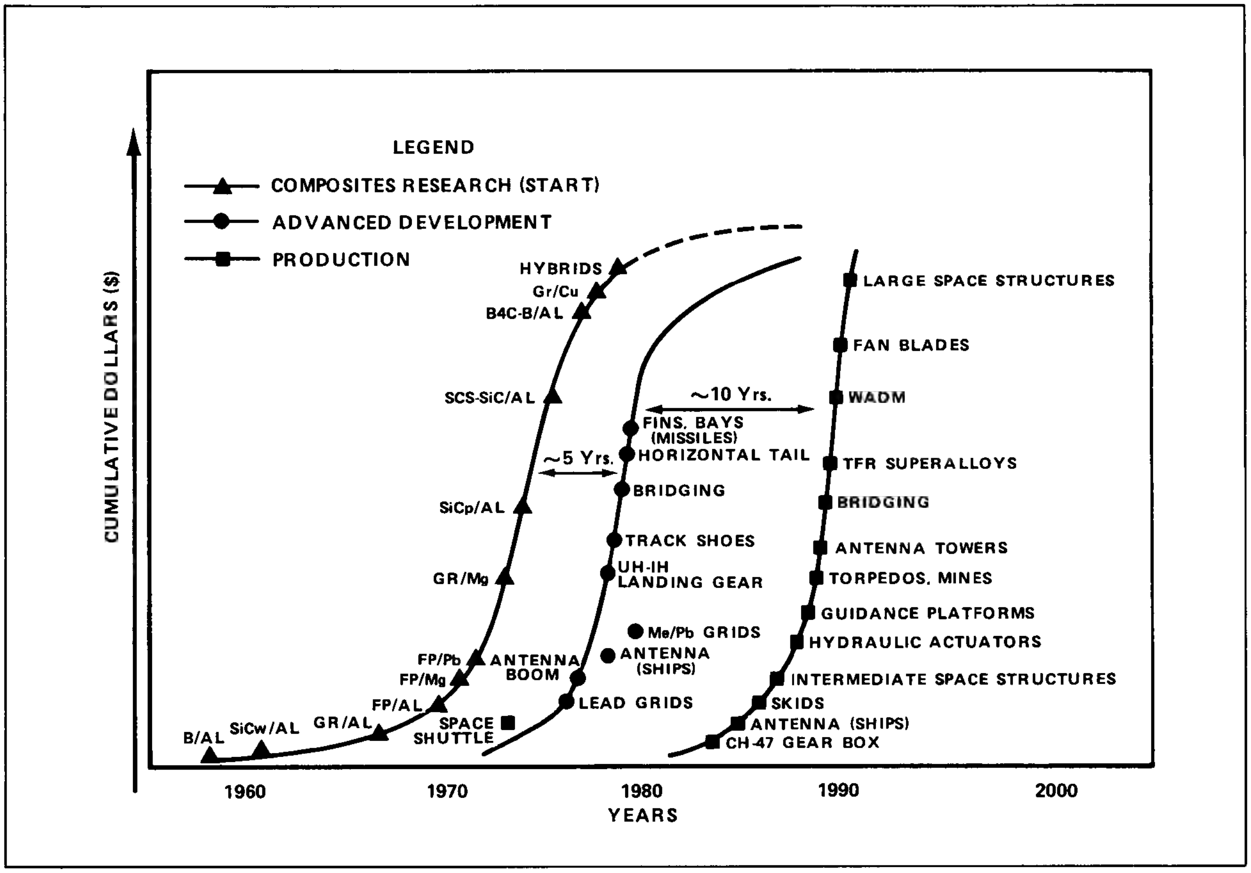

Figure 12. Department of Defense Metal Matrix Composites Development

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In the area of ceramic matrix composites, the United States has foreseen a fundamental strength for the future. Table 6 depicts many of the potential applications and their relative time frame of existence. The time frame ranges from near term (0-2 years) to far term (20 years).

Free World Applications. France has progressed rapidly since the early 1970s in applying composite theory to actual use. The two leading aircraft manufacturers, Dassault and Aerospatiale, with the aid of their government have embarked on a goal to produce an all-composite aircraft. The original 1979 goal was three to five years for secondary structures, five to eight years for primary structures, and 10 years for a complete airfoil to replace an existing wing already in service. The exact status of this program is not known.

As early as 1972, the French decided to launch a study of a boron composite horizontal stabilizer for the Mirage F-1. This stabilizer apparently became too expensive and presented unnecessary machining problems, and the program was abandoned. In 1974, commercial carbon fibers were successfully planned for use as control surfaces of the Mirage III, debuting in 1975.

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The Mirage 2000 and Super Mirage 4000 programs have both been quite significant in composites development. The Mirage 2000 has 17 primary and secondary components made of either boron or carbon

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composites. They include the landing-gear doors, gear hatches, gear hold covers, radio bay doors, flaps, the stabilizer box, and control surfaces. The Mirage 4000 uses a canard with a carbon fiber surface and honeycomb filling. It also has composite flaps (identical to the Mirage 2000) and vertical stabilizer. The vertical stabilizer was the first French element made of monolithic panels. The stabilizer has two self-stiffening surfaces (integrally stiffened) lying on a substructure composed of longerons and raised aluminum bands. Connections are made by screws and Jo-bolts.

French manufacturers, notably Dassault and Aerospatiale, are committed to the massive use of carbon composites on aircraft. They have clear thoughts on creating an all-composite plane, as noted earlier, and have achieved results toward that goal with primary and secondary structures on the Mirage 2000 and integral stiffening on the Mirage 4000

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The West Germans have conducted similar studies involving composites on the Tornado. Messerschmidt-Boelkow-Blohm has fabricated a composite forward fuselage (figure 13), horizontal stabilizers, and wings. The German goal is an all-composite fighter aircraft.

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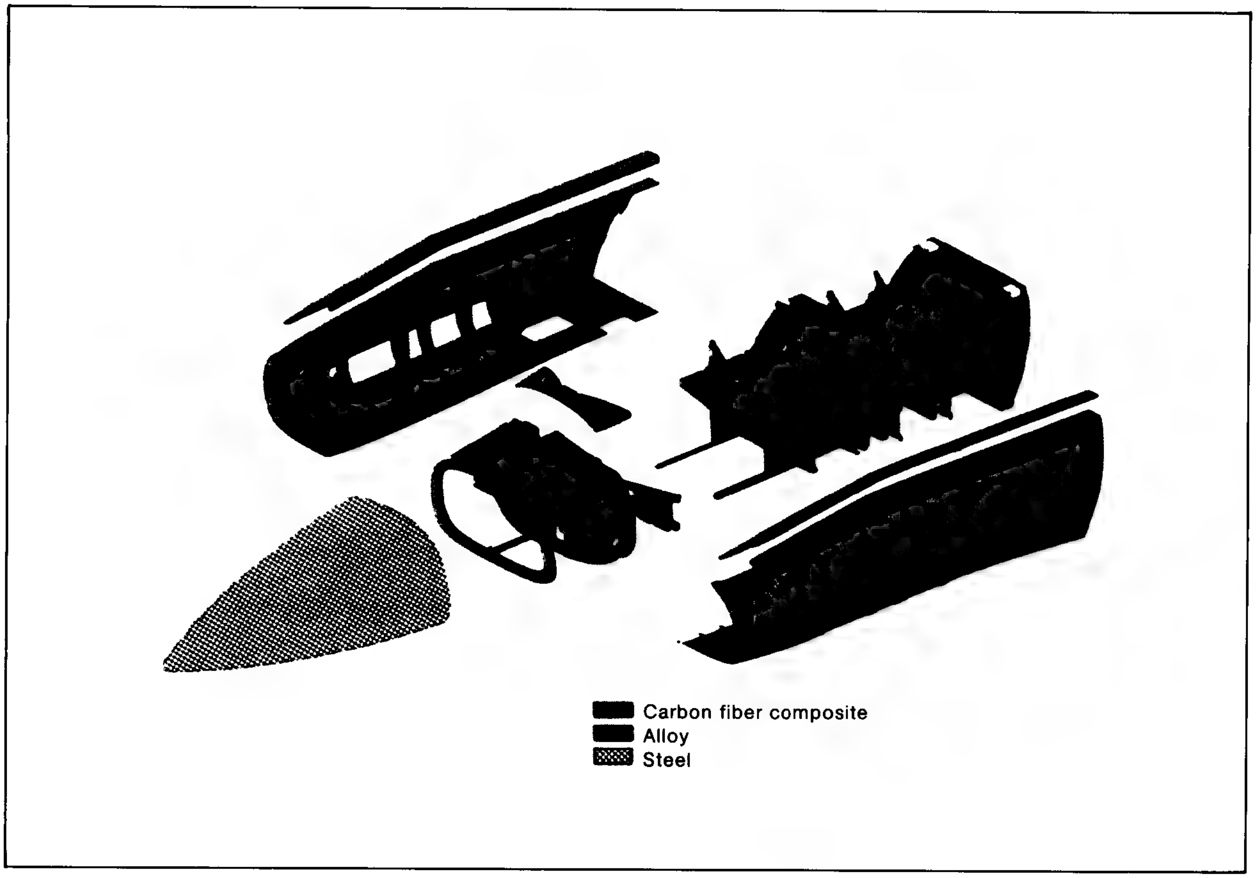

Figure 13. Forward Fuselage Development for Tornado 25X1

The helicopter rotor blade is an application where the French have made great strides in adapting composites to traditionally metal components. Aerospatiale, with more than 20 years experience in composite rotor blade production, makes virtually all its new and replacement blades with composite material. The SA-341 Gazelle, SA-330 Puma, SA-360 Dauphin, AS-350 Ecureuil/Astar, and AS-355 Ecureuil-2/Twinstar all have composite blades. As for rotor hubs, the Starflex hub has been produced from a glass-reinforced elastomer for the Dauphin and the Ecureuils; the Triflex hub will also be composed of graphite/elastomer composite. 25X1

In the area of small, private aircraft, Finland's PIK-23 (figure 14) is reported to be an all-composite aircraft using primarily graphite/epoxy. 25X1

Carbon/carbon composites, because of their high-temperature adaptability, are quite suitable for use as components of brakes. Two French firms, Messier and Sepcarb, are both involved in providing carbon/carbon disks for the Mirage 2000. Dunlop supplies carbon/carbon brakes for the Concorde, and Sepcarb is currently testing carbon/carbon rotor brakes on the Super Frelon. 25X1

Advanced composite materials, which have already been used by Airbus Industrie to obtain a 400-kg overall weight savings on the A-310 medium-range passenger aircraft, are now being considered by the

Figure 14. Finland's PIK-23 25X1

European manufacturing consortium for trimming an additional 2,000 kg from the planned short-range A-320 aircraft. This will be accomplished by using primarily carbon and aramid (Kevlar) fibers.

The consortium's overall planning will be divided among its members; France's Societe Nationale des Industries Aerospatiales (SNIAS), West Germany's Messerschmidt Boelkow Blohm, Spain's CASA, British Aerospace, and Holland's Fokker. The last two companies are believed to be the most experienced in the use of composites, mainly as the result of coproduction agreements between Fokker and General Dynamics for the F-16 aircraft and the development by British Aerospace of its AV-8B short takeoff and landing aircraft. Progress beyond the planning stage of the A-320 and into the development program will depend heavily on government support, since no single aircraft manufacturer will be able to fund the high cost.

Of the weight savings obtained from composites on the A-310, 100 kg were obtained from the use of aramid fibers, 150 kg from carbon fibers, and 145 kg from hybrid composites including aramid/glass and carbon/aramid. By 1990, Airbus Industrie estimates that utilization of advanced composites for increasingly higher loaded, or primary structures, could reach 20 percent or more of the structural weight of aircraft.

The main market for carbon fibers over the next two years will be in Italy, where Aeritalia is building structures for the Boeing 767. Much of this market is likely to shift to France because of the rapid development of French applications for civil and military aircraft. 25X1

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In Japan, Mitsubishi Aircraft, Kawasaki, and Fuji Aircraft have all been involved in aircraft production and repairs programs. Mitsubishi has fabricated, from Toray 8H satin woven fabric prepreg, a nose landing gear of apparent high quality for the Japanese T-2 trainer aircraft. The canard, also built by Mitsubishi, of the controlled configuration version of the T-2 (CCVT-2) employs graphite/epoxy composites. The cooperative development of the C-1 cargo aircraft horizontal stabilizer (with the National Aerospace Laboratory) represents a giant step forward in primary composite structures for Japan. This will provide them with considerable design and manufacturing experience with complex parts and co-curing of large sections. Carbon/aluminum metal matrix composites were studied at Mitsubishi but were discontinued because of problems with the carbon/aluminum interface. They are, however, enthusiastic about SiC fibers in both aluminum and epoxy matrices. 25X1

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Kawasaki's history of composite technology dates back to 1970 when they began producing carbon/epoxy cylinders for nuclear reactor fuel centrifuges. One of their most advanced composite aircraft components is the spoiler for the C-1 cargo aircraft. The C-1 spoiler involved a substantial engineering and manufacturing effort with verification testing and operational experience. This development was sponsored by the Japan Defense Agency. The component consists of an aluminum honeycomb core with upper and lower skin as well as the spar and end fittings of carbon/epoxy. [redacted]

Some of Kawasaki's recent work on carbon/epoxy has included development of the main structure for the MTX, a jet trainer similar to the US Navy VTX. They have also investigated polyimide resins for the high-temperature areas of short takeoff and landing aircraft. Kawasaki has two autoclaves each about 4.3 meters in diameter and 12.2 meters long and capable of handling four trays of bonded or composite components. [redacted]

Composite materials are currently in production at Fuji Aircraft. Fuji has a contract to manufacture the upper and lower rudder and tab sections for the Bowing 747. These have a glass-Nomex core. Their experience with graphite composites began with the Boeing 767 program. Hybrid composites of Kevlar and graphite are fabricated for the 767 landing gear doors with the outer skin consisting of one ply of Kevlar/epoxy. All materials are supplied by the US Hexcel Corporation to Boeing specifications. Fuji has installed an autoclave (5 meters by 9 meters) capable of temperatures to 175°C and pressures of 690 MPa. This unit was designed and built by Fuji and is housed in a new environmentally controlled building that is dedicated to the Boeing 767 production. There are also two other smaller autoclaves at Fuji in areas not environmentally controlled. [redacted]

[redacted]

Status of Other Communist Countries

People's Republic of China

Deficiencies in the production of conventional materials have not prevented the Chinese from initiating work in advanced materials such as composites. Research work in composites is being done at the Institute of Chemistry and at the Institute of Mechanics, both in Beijing. Applied work is carried out at the Beijing Research Institute of Materials, the Northwest Chemical Propulsion Corporation, and the Beijing Institute of Aeronautical Materials. University research is also under way. The Chinese effort in composite materials is 10 to 15 years behind that of the United States with respect to both production and fabrication. The Cultural Revolution of 1966-69 resulted in the loss of a generation of technologists, but the Chinese research manpower pool is still impressive in both quantity and quality. Western literature is followed very closely in an attempt to avoid research problems that others have already encountered and solved. Possibly the greatest obstacle to Chinese technical advancement is the lack of funds with which to purchase materials, equipment, facilities, and technology. [redacted]

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Composites research has been progressing in China for over 10 years. According to Chinese literature, testing of moisture effects on graphite/epoxy began in 1973, and some aircraft secondary structures have been in flight test since at least 1977. [redacted]

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At a facility near Beijing, a graphite/epoxy vertical stabilizer is being designed for a second fighter aircraft. The rear spar is a graphite/epoxy C-channel about 15 to 20 cm deep and about 20 to 30 plies thick. [redacted]

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As early as 1978, the Chinese were making silicon carbide fibers.

The Institute of Chemistry has developed a heat resistant fiber of reinforced modified phenol formaldehyde resin. A phenolic novolac was converted to a resin and cured with glass reinforcement under low pressure. It was inferred from the composition, molding requirements, and properties that the system could be used for making nose cones of large rockets 25X1

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While the Chinese properties appear lower than those of the United States, the difference in fiber volumes should be noted. If the properties are adjusted for fiber volume, the Chinese material is only slightly inferior to that of the United States, and fiber volume is relatively easy to increase in organic matrix composites

The Chinese have reported the development of an aramid fiber which they have designated Fiber B. The designation suggests that it was based upon DuPont data for its Kevlar test product. It is suggested that difficulty in commercial production may be encountered because of the difficulty of obtaining raw materials of the required purity. The properties of Fiber B are intermediate between Kevlar 29 and 49. Accordingly, it lacks the stiffness desired for high-strength composites parts for aircraft, missiles, and ships. China can be expected to continue development of a stronger fiber.

The Chinese have shown an intense interest in applying composites to aerospace systems, but limited production capabilities are impeding them. At least one large filament winding machine has been imported from West Germany; two others, one from the United States, have been ordered. These units will have a capability to wind structures up to 5 meters in diameter by 18 meters long with a 200-mm wall thickness; the machines are capable of handling glass, aramid, or graphite fibers. 25X1

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[redacted]

It appears that considerable emphasis is being placed on the use of glass-reinforced plastics. As early as 1963 the Chinese were experimenting with composite applications to hulls for torpedo boats approximately 15.3 meters long, tubular objects 300 mm in diameter by 6.1 meters long, radar dishes 6.1 meters in diameter, military helmets, and armor for tanks and gun mounts [redacted]

European Communist Countries

Technical literature about non-Soviet ECC composites research indicates a close connection to that of the USSR. In most cases the satellite countries provide basic research and materials to the USSR. [redacted]

East Germany. East German composites research appears to be aimed at supplementing Soviet research in MMC and in NDT. The Soviet and East German literature contains references to work occurring at the A. A. Baykov Institute of Metallurgy in Moscow on graphite/copper composites. In addition, a program involving East Germans, Poles, Hungarians, and Soviets involves investigating exoelectron emissions and their application to NDT of composites and other materials; [redacted]

Poland. The Polish composites program is possibly the most advanced of the satellite country efforts. Basic research is under way in the areas of exoelectron emission NDT techniques, as noted above, and on coatings to protect the fiber from interacting with the matrix in MMC. In addition the Poles have developed glass/epoxy rotor blades for the MI-2 and W-3 helicopters. The Polish-built Jaguar tank, like the Soviet T-72, will incorporate a glass/phenolic laminate in the upper glacis armor. It is assumed that Polish glass fiber production is used to supplement that of the USSR. [redacted] 25X1 25X1

Hungary. The Hungarian composites effort may also be directed at supplementing Soviet efforts—in this case, for special filaments. The Hungarians are producing nickel wires and alumina fibers on an unknown scale. In addition they are also investigating exoelectron emission NDT techniques. [redacted] 25X1

Czechoslovakia. The Czech composites effort appears to be primarily devoted to glass fibers. Production of glass fibers is sufficient to provide a major export item that is sold worldwide and that must obviously supplement the composites efforts of the other Warsaw Pact nations. [redacted] 25X1 25X1 25X1

Romania. Whatever composites research occurs in Romania is probably conducted at the Bucharest Chemical Research Institute (ICECHIM) and subordinate or associated institutes. ICECHIM has departments that study resins and synthetic fibers. [redacted] 25X1 25X1

Bulgaria. [redacted] on 9 October 1981 the Bulgarian press announced that the Central Institute of the Chemical Industry and associated institutes have designed and built a fiberglass bridge over the Nishava River; the bridge is reported to be capable of carrying a load of 1,200 tonnes. [redacted] 25X1 25X1 25X1 25X1 25X1

Prospects for Advance

Prospects for USSR Advance

The Soviets are projecting a significant expansion in production capabilities for the various components necessary for composites fabrication. These increases

are projected on the basis of improvements in mechanization, in control instrumentation, and in labor efficiency. These manufacturing improvements probably will be implemented because the high priority given to composites by the XXV Congress of the CPSU in 1975 continues today. In 1981 a high priority was given to robotics that should provide benefits to composites fabrication as well as to other areas of Soviet industry. [redacted]

The Soviet manufacturing development of composites has suffered in the past from a lack of consumer applications; this should change to some extent with the advent of composites fishing rods, track and field equipment, and automotive parts. The increased production experience created by these consumer uses should provide the Soviets with the opportunity to expand the usage of composites to new military fields. Thus, research in the stability of thin, stiffened, composites cylindrical shells could result in a graphite/epoxy missile structure similar to concepts being studied in the United States [redacted] Likewise, Soviet research into the ablation and erosion characteristics of carbon fiber–reinforced plastics and of carbon/carbon composites suggests advanced reentry vehicle design requirements of the kind currently in the US [redacted]

The Soviet composites research program will continue to be recognized by Soviet military R&D planners within the Ministry of Defense as a militarily important technology area necessary for increasing the performance of numerous combat systems. All types of composites will be investigated as possible solutions to solving existing materials problems, such as fatigue and stiffness. The area of composites technology that will experience the greatest progress is that of manufacturing technology. This progress will be achieved by the training of a skilled work force and by the increased use of automated equipment. [redacted]

Prospects for Free World Advance

In the European composites arena, the technology base has been moving steadily forward. Much of the US basic understanding of composites had its beginnings in Europe, and the mutual transference of new insights still exists. Among certain US composites experts there is a belief that, because of their technical capabilities, an aggressive European advance, such as the all-composite aircraft noted above, could leapfrog the United States in composites production within three years. [redacted] 25X1

A consortium of European countries are considering designs (predominantly sweptwing, canard configurations) of a fighter aircraft comparable in sophistication to the F-16XL. Preliminary designs have the potential of 60 to 80 percent empty structural weight of graphite/epoxy composites (figure 15). Within the agreement, England would build the wing, Italy the empennage, and France or Germany the forward fuselage. [redacted] 25X1 25X1

The Israeli company, IAI, is working in conjunction with Grumman Aerospace Corporation to design a new air-superiority fighter called the Lavi. The aircraft is expected to be as much as 60 percent graphite/epoxy [redacted] 25X1 25X1 25X1

Prospects for Chinese Advance

Chinese composites researchers have been characterized as very well-informed on composites research occurring around the world; their primary disadvantage appears to be a lack of equipment with which to conduct their research. Efforts have been made to alleviate this deficiency by purchasing Free World equipment, but a lack of hard currency has limited the effectiveness of these efforts. Because of these economic considerations, the Chinese have indicated a willingness to take shortcuts in an effort to get composites into production as quickly as possible. Thus, Chinese progress in the next 10 years will probably occur through the acquisition of equipment for the manufacturing of organic matrix composites. MMC and ceramic matrix research will probably have a relatively low priority in China for the next 3 to 5 years. [redacted] 25X1 25X1 25X1

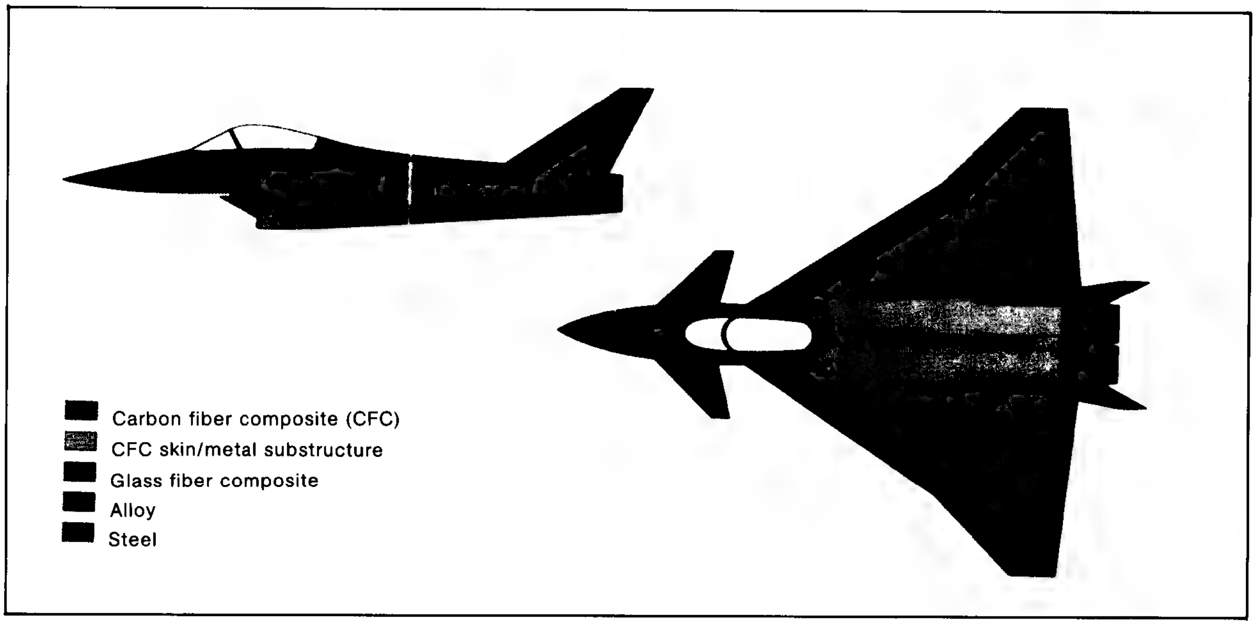

Figure 15. European Fighter of the 1990s (Agile Combat Aircraft)

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Technology Transfer

Western industrialized countries are the acknowledged leaders in composites development and application. Because many of the applications offer considerable potential for improving the performance and reliability of military systems, the USSR and China have attempted to close this gap through technology transfer. Technology acquisition may be covert or through open trade channels involving the knowledge of conceptual design and technical know-how, purchase of manufacturing and fabrication equipment, and the acquisition of key end products. The USSR, in particular, sees technology transfer as a means to reduce costs of unfruitful R&D, to reduce development programs by using proven technology, to focus on performance specifications of known adversary military systems, and to upgrade the performance of indigenous military systems. The primary challenge to the recipient countries will be their ability to assimilate composites technology without the benefit of the R&D experience comparable to that developed in the West.

The Soviets are avid followers of Western literature; they feel that monitoring foreign research is an efficient means of complementing their own reserch programs. At the Third All-Union Conference on Composite Materials in 1972, S. Ye. Salibekov discussed the fact that a review of US literature concerning fiber/matrix interactions in metal matrix composites had led to a Soviet program on applying nickel coatings on graphite fibers for graphite/aluminum composites. Likewise, at the Fourth All-Union Conference in 1978, Salibekov discussed his adaptation of the US Aerospace Corporation process for the spontaneous impregnation of graphite fibers with aluminum. 25X1

The area of carbon/carbon technology transfer has received a large amount of attention since 1979. The Soviets are investigating carbon/carbon throat inserts for rocket nozzles, but they do not yet have the

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capability to produce large billets (200 to 250 kg) like those produced in the United States and in France for rocket nozzles and for shape-stable nose tips. As in the Soviet approach to other technologies, the USSR has attempted to purchase carbon/carbon technology and equipment. Western literature and conferences have been exploited; Western experts, [redacted] have been the guests of the USSR; and necessary equipment and technology, like 137.9 MPa (20,000 psi) hot isostatic presses, have been purchased from Sweden, France, and the United States by the USSR and its Warsaw Pact allies expressly for carbon/carbon research [redacted] The Soviets can be expected to strive for self-sufficiency in carbon/carbon composites by conducting their own research and by continuing to exploit Western technology and equipment. [redacted]

In trying to assess the Soviet progress in advanced composites, a transaction that took place in the summer of 1978 is very revealing. A West German firm that manufactures autoclaves for the production of composites structures sold 40 autoclaves to the USSR. The autoclaves, which were 5 meters in diameter and 15 meters in length, were ideal for producing aircraft wing structures. [redacted] it appeared the Soviets were aggressively developing their composite material production capability. These autoclaves, as well as the presses cited above, are well within the fabrication capability of the USSR, but acquisition might have been delayed up to several years if Soviet plants had been used to produce this equipment. [redacted] 25X1

Soviet R&D on aramids is aided by the military need for high performance composite materials. The object of much of the Soviet effort has been to develop an aramid fiber which shares the high strength characteristics of DuPont's Kevlar. Evidence now is available that the Soviets have developed an aramid fiber that is being used in the manufacture of body armor. In addition they have been testing aramid-wound solid rocket motor cases for strategic missiles. There are indications that much of the Soviet aramid fiber technology is based on US technology. [redacted]

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Technical Comparisons

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USSR Versus US Comparison

The Soviets appear to be spending more R&D funds on metal matrix composites (MMC) than the United States, but the results obtained do not appear to be proportionately greater. Both the USSR and the United States are working on MMC for the same reason—increased performance of military systems. Both recognize cost as the major implementation problem and fiber/matrix interaction as the major technical problem. The Soviets appear to have developed a pultrusion capability that exceeds that of the

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United States, and they have a greater capability to produce thin metallic foils necessary for the production of MMC. The Soviets appear to have performed more work than the United States on ultrahigh temperature MMC, which would have applications in aircraft engines. The Soviet analytical capabilities for determining temperature and pressure diffusion bonding parameters exceeds those of the United States. However, in practice the Soviet's graphite/aluminum and graphite/magnesium data do not have the property translation efficiency that the US materials do. The Soviets do not appear to be developing materials, processes, and design methodologies for specific applications as in the United States (although such information is likely to be restricted). The United States is developing alumina/lead and titanium/lead for submarine batteries, graphite/aluminum for Army transportable bridges, Al_2O_3 fiber/magnesium composites for helicopter transmission cases, graphite/magnesium for dimensionally stable space structures, borsic/titanium for engine fan blades, and silicon carbide reinforced, superplastically formed, diffusion bonded titanium for airframes. Further, the United States is producing boron/aluminum struts for the space shuttle. Overall, the Soviets have accomplished much and are doing a greater amount of work than the United States, but much of this work is fundamental.

The Soviet advanced composites program appears to be well coordinated. While the Soviets apparently lag the United States in the automation of composites fabrication, their manufacturing technology—while not very efficient—is adequate to support the relatively widespread application of composites to prototype systems. Thus, while continuing to lag slightly behind the United States, the Soviets appear to have attained a state of near parity in composites technology. Although US investment in automated fabrication of composites could widen this gap, technical parity is considered to exist for composites in general and reflects several technical leads by both countries. The US still leads in such areas as carbon/carbon technology, automated fabrication, and fiber production process controls, while the USSR leads in such areas as MMC technology, fiber production capacity, and high-temperature organic matrix research. In confirmed production applications, the United States still enjoys a sizable lead.

The Soviets are probably the first in the world to incorporate an organic matrix composite in a tank armor system. This is significant, since they are usually depicted as being ultraconservative in the use of new materials and technologies. 25X1

Free World Versus US Comparison

Comparison of US state-of-the-art composite technology and several Free World countries are presented in this section. The information gathered for this comparison was obtained from more than 80 industry and government organizations in the United States, Japan, and Europe. 25X1

Figure 16 relates the ranking of each country in each of the major areas of composite activity (materials and technology). The figure was prepared from extensive research by the Institute for Defense Analysis (IDA) for the Department of Defense in 1981. The size of the squares indicates the relative standing in each area. In some cases, little or no information was available and is indicated by a blank. Obviously, such an assessment is subjective, but we believe that this assessment represents the overall relative capability reasonably well. 25X1

Figure 16-A shows that the United States has the major capability for rayon precursor and pitch precursor for carbon fibers, while Japan leads the world in PAN precursor. A similar relationship exists between the carbon fibers produced from these precursors. However, the US capability in PAN carbon fiber production and technology is now second only to that of Japan. The United States is the major custodian of aramid technology, but a growing capability apparently exists in the USSR. 25X1

Activity in other fibers is considerably less than in carbon fibers. Boron fiber technology is primarily centered in the United States. The B&C coating process used in the United States was licensed from France, although French boron fiber production is virtually nil. Silicon carbide deposition process fiber technology results in fibers approximately 0.13-0.20 mm in diameter and is essentially contained in

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the United States. The substrateless micron-size silicon carbide fibers derived from polycarbosilane are almost solely Japanese, although some research work is in progress in the United States. The smaller diameter Japanese fibers have many advantages in metal infiltration and uniformity of matrix. Alumina fibers of two types are being developed—the high-purity FP fiber, which is a US product entirely, and the less pure alumina, which is a Japanese development.

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